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Micro-Black-Holes as intermediate states in the formation of Extended Air Showers

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Summary. — One of the consequences of the existence of extra-dimensions and TeV-scale gravity would be the production of Micro-Black-Holes (MBH) in the central collisions of two particles with high enough energy. A natural scenario to investigate this hypothesis is provided by the collisions of cosmic ray particles belonging to the ultra-high-energy tail of the cosmic ray spectrum, interacting with the Earth's atmosphere and originating, as a consequence, extended air showers (EAS). In this paper we present insights on the effects of intermediate MBH states on typical EAS features, on the basis of theoretical simulations by state-of-the-art event generators for describing the MBH formation and evaporation processes, followed by the propagation of the emitted elementary particles and hadrons in the atmosphere.

PACS `11.10.Kk` – field theories in dimensions other than four.
PACS `04.50.Gh` – higher-dimensional black holes, black strings and related objects.
PACS `96.50.S-` – cosmic rays.
PACS `13.85.Tp` – cosmic ray interactions.

1. – Introduction

One of the proposals for reconciling the large difference observed between the typical scale of electroweak (EW) interactions and the gravitational Planck scale, *i.e.* to solve the scale hierarchy problem, was the introduction of the hypothesis of extra-dimensions accompanied by TeV-gravity models [1-3]. In particular, according to the scenarios of refs. [1, 2], gravity appears so weak in our 4-dimensional world with respect to the other interactions, just because its quantum carrier, the graviton, mainly propagates in n additional large extra-dimensions, whereas the propagators of the other gauge bosons, as well as the other fermions, are confined on our 4-dimensional brane. If this is the case, one can introduce a fundamental gravity scale determining the intensity of the interaction in $d = 4 + n$ dimensions (the bulk), that, in line of principle, could be as low

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as the scales of the other fundamental interactions. This implies that in d-dimensions gravity could be as strong as Standard Model (SM) interactions, meaning that it has to be accounted for in the description of high-energy elementary-particle collisions, whereas in our present 4-dimensional microscopic simulations it is ordinarily neglected.

The possible formation of Micro-Black-Holes (MBHs) in high-energy collisions may be one of the most relevant phenomenological consequences of the aforementioned theoretical hypothesis [4-7]. It is thus important to search for MBHs from the experimental point of view, in order to get insights and constraints on the possible values of a fundamental gravity scale and the existence of extra dimensions. However, if MBHs exist, they evaporate in a very short amount of time (of the order of $\sim 10^{-26}$ s, oppositely to macroscopic black holes, which are long-lived), meaning that their possible formation has to be inferred indirectly from the observation of the radiation they emit.

Actually, such kinds of searches have recently been carried out by the experimental collaborations at the Large Hadron Collider (LHC) at CERN, using data on proton-proton (p-p) collisions up to $\sqrt{s} = 8\,\text{TeV}$ energies, the present maximum center-of-mass (CM) energy reached in a hadron collider. The results have not showed any sizable deviation from the Standard Model (SM) scenario, at least so far, implying lower limits on the fundamental gravity scale of at least a few TeV. However, the hypothesis that MBHs can appear in higher-energy collisions is not ruled out, and the systematical investigation of their possible formation in the interactions of Ultra-High-Energy Cosmic Rays (UHECRs) with the Earth's atmosphere, with CM energies well beyond those within reach presently at accelerators, is still at the beginning. This work aims at the description of our first efforts in this direction, showing results of theoretical simulations of extended air showers (EAS) obtained under the hypothesis of MBH formation, as steps of a more articulated project aiming at a final comparison with astrophysical experimental data.

This paper is organized as follows. After presenting in sect. **2** a short review of MBH searches at LHC, which at present provide the most severe lower bounds on the mass of these objects, we describe our steps towards a systematical study of MBH formation and evaporation in EAS in sect. **3**, followed by examples of the results that can be obtained in the numerical framework we have built in sect. **4**, a discussion on specific signatures worth of investigation in sect. **5** and our conclusions in sect. **6**.

2. – Searches for MBHs at LHC

Both the ATLAS and CMS Collaborations have searched for MBH formation and evaporation at LHC, in the framework of the so-called "searches for exotica", using data available from p-p collisions at both 7 and 8 TeV CM energies [8-13].

In particular, the CMS searches of last year [12] have focused on events with several mutually isolated hard objects (jets, leptons and photons), by looking at the scalar sum H_T of their transverse momenta, as a function of their multiplicity per event. The data have been compared to the results of theoretical simulations performed with the most recent publicly available Monte Carlo (MC) event generators for the formation and evaporation of MBHs, considering both the non-rotating and the rotating case. While these generators predict an excess of events in the tails of the H_T distributions with respect to the SM expectations, so far the data have not shown any significant deviation from the SM background, dominated by QCD production. This has bounded the MBH minimal mass from below in the range $M_{MBH,min} > 4.3$–$6.2\,\text{TeV}$, depending on the gravity scenario (either purely semiclassical, as available in the `BlackMax` generator [14], or including quantum corrections, as offered by the `QBH` code [15]) and on the input parameters of the simulations (among the others, we mention the number of extra-dimensions, the tension of the brane and the amount of MBH rotation, the MBH mass, the loss and suppression factors).

On the other hand, the ATLAS Collaboration, after an investigation of the lepton+jets final state in ref. [10], recently looked for the yield of events with a same-sign di-muon signature as a function of the total multiplicity N_{TRK} of inner tracks [13]. While, in case of an intermediate MBH stage, an excess of these events (with transverse momentum of the leading muon $> 100\,\mathrm{GeV}$) is expected especially at larger N_{TRK}, the results show very good agreement with the SM background, mainly originated by $t\bar{t}$, diboson and W + jets production. This, in turn, implies a lower limit $M_{MBH,min} > 5.1$–$5.7\,\mathrm{TeV}$, depending on the scenarios. ATLAS limits show compatibility with those observed by CMS being the most severe presently available constraints from below on MBH masses.

Especially at their beginning, the experimental analyses searching for MBHs at LHC have received some criticisms (see, *e.g.*, the discussion in ref. [16]) because they were concluded on the basis of predictions by means of semi-classical MC event generators like `BlackMax` or `CHARYBDIS` [17, 18] that, although originally targeted at LHC, would not be the optimal choice at the relatively low CM energy reached so far, where it is expected that Quantum Gravity effects cannot be neglected if the fundamental gravity scale is close enough to the EW symmetry breaking scale, *i.e.* in the TeV region. However, as already pointed out above, even after introducing in the analysis procedure the only publicly available event generator already including some quantum effects, `QBH`, the CMS Collaboration still does not find signals of the presence of MBHs in the data. It will be interesting indeed to update these analyses during the next run of LHC, when the CM energy will be upgraded to 13 TeV.

3. – MBHs as intermediate steps in the formation of Extended Air Showers

As pointed out in the introduction, the interactions of the galactic and extra-galactic UHECRs impinging on the Earth with its atmosphere may correspond to CM energies even higher than those reached at LHC. Thus the observation and detection of UHECRs provides a natural laboratory, offered by astrophysics, to test for effects of Physics beyond the SM and the possible formation of intermediate MBHs.

Actually, UHECRs give generally rise to extended air showers (EAS) characterized by both an electromagnetic and a hadronic component, whose lateral profiles evolve with increasing atmospheric depths. The detection of these components can be performed by combined techniques, involving both measurements of secondary particles impinging on a relatively extended portion of the Earth's surface, and measurements of the fluorescence light emitted in the sky at different atmospheric depths. One of the active experiments exploiting these techniques and their combination is the Pierre Auger Observatory (PAO) [19], that has collected statistics on EAS generated by cosmic ray primaries with energies from $> 10^{18}\,\mathrm{eV}$ up to $\sim 10^{20}\,\mathrm{eV}$ in the laboratory frame (corresponding to a minimum and a maximum energy of a few ten TeV and $\sim 400\,\mathrm{TeV}$ in the p-p CM frame, respectively), from years of observations. The data have confirmed the presence of an ankle in the primary spectrum at $\sim 10^{18.6}\,\mathrm{eV}$, whose cause is still under debate, and a strong suppression of the flux at energies $> 10^{19.6}\,\mathrm{eV}$, where very few EAS have been detected. Other UHECR properties like their origin, acceleration mechanisms and composition, are still under discussion [20].

Notwithstanding the ongoing efforts in this direction, not all EAS properties can be inferred yet just by measurements, at least using the present detection techniques. Thus, the results of the measurements are typically compared with those from MC simulation packages, including both electromagnetic and hadronic interaction models, whose parameter values are continuously tuned and extrapolated at high energies on the basis of the latest available accelerator results, and models for the transport of particles between subsequent interactions depending on the atmospheric profile and other details. The most updated and widely adopted framework for making this kind of simulations is offered by the `CORSIKA` package [21], including a collection of low- and high-energy interaction models, that can be combined in various ways for simulating EAS in different geometries and atmospheric conditions and compositions.

In this work, we have modified the `CORSIKA` framework in such a way we can account for a transient MBH state, which could be formed during the initial hard-scattering of a primary cosmic ray with a nucleon of the Earth's atmosphere. As a first approximation, we have neglected nuclear effects, *i.e.* we have assumed a p-p interaction leading to a transient MBH which, after experiencing the balding and spin-down phases [6, 16], evaporates, by emitting Hawking radiation [22] in a large number of particle degrees of freedom (leptons and quarks, gauge bosons, gravitons). This emission is corrected by grey-body factors, encoding gravitational effects related to the curvature of the geometry near the MBH event horizon [23, 24]. It is expected that most of the radiation (at least 90%) is confined on the brane, although the percentage of gravitons emitted in the bulk increase with the number of extra-dimensions, reaching values around $\sim 25\%$ in spaces with $d = 11$ [25]. The SM products of the MBH evaporation have then been evolved according to a Parton and Photon Shower approach up to hadronization and hadron decay, and the resulting final hadrons and leptons have been injected in `CORSIKA`, allowing for their simultaneous evolution through secondary interactions and propagation in the atmosphere according to the various models available in `CORSIKA`.

The steps of our simulation setup from the primary interaction up to detection at the Earth's surface are schematized in fig. 1, where the MC event generators used for each step are also mentioned. In practice, we have reached a good level of automation by setting up a complex interface between different MC event generators: the `BlackMax` code for generating and evaporating MBHs, the `PYTHIA` [26-28] and `HERWIG` [29, 30] Shower MC codes for generating parton and photon shower, hadronization and hadron decay, the `CORSIKA` computing framework to evolve simultaneously the resulting hadrons and leptons by generating their secondary interactions and by transporting them in the atmosphere. `CORSIKA` has been used as well for sampling the atmospheric depth of the primary first interaction. Although this framework is still prone to extensions and refinements (in particular we think it could be important to extend it in order to account for nuclear effects in the primary collisions, taking into account both that the atmospheric protons are bounded in nuclei and that primary cosmic rays could be ions, instead of protons), we would like to point out that, as far as we know, this is the first time that modern MBH event generators used for LHC are extended to the astrophysics context and interfaced in such a complex tool. Although in the past there were already some numerical studies on the hypothesis of MBH formation in cosmic ray interactions [31], they relied on a more simplified framework not involving public codes as complex as those mentioned above, that are nowadays also continuously tuned to the most recent LHC results.

4. – Results of our theoretical simulations

In this section we collect and discuss selected results of our simulations. In particular, we tried to understand if and how an intermediate transient MBH stage can

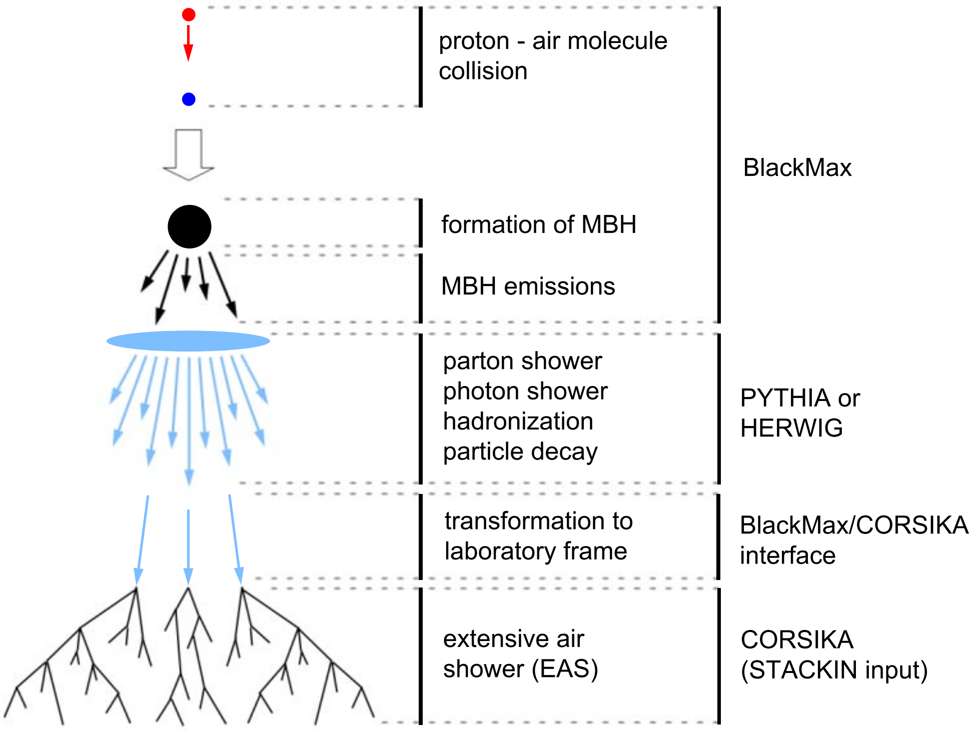

Fig. 1. – Steps of our simulation setup, together with the indication of the Monte Carlo event generators used for each of them.

modify EAS features. At this aim, we compared three sets of EAS events: the first set (set I) was obtained by the full simulation chain described above, including the formation of a transient MBH state, followed by parton shower and air shower development, whereas the second set (set II) includes EAS generated according to the standard scenario, where a primary cosmic ray proton interacts with the Earth's atmosphere according to the SM physics without the possibility of originating any MBH. Last, a third set (set III) includes EAS generated according to the standard scenario by primary iron nuclei (^{56}Fe). In particular, the events of set I were obtained by running `BlackMax` + `PYTHIA` + `CORSIKA`, whereas the events of set II and III were obtained by `CORSIKA` only, version 7.37, using `QGSJET-II` [32-34] as hadronic interaction model at energies above 80 GeV and `FLUKA` [35-37] (version 2011.2b) as hadronic interaction model at lower energies. We generated $\sim$ 100 EAS events for each of the three cases, adopting the following input conditions: we considered primary CR protons with partonic distributions according to the `Cteq6LL` parton distribution functions from the `LHAPDF` interface [38] and with a laboratory energy of 10^{18} eV, impinging on protons approximated as freely moving in atmospheric nuclei, corresponding to a *p*-*p* CM energy $\sqrt{s} \simeq 43\,\mathrm{TeV}$, in a $(d = 4 + 2)$-dimensional scenario, where we fixed the fundamental gravity scale to 5 TeV and we allowed for the formation of MBHs with a mass in the range $10\,\mathrm{TeV} < m_{MBH} < \sqrt{s}$, with mass, momentum and angular-momentum loss factors fixed to 0.15 and with charge, color and angular-momentum suppression factors fixed to 0.2.

All possible SM particle degrees of freedom were allowed to be evaporated by MBHs, together with gravitons. The SM evaporation products were further evolved by means of the fortran `PYTHIA` version 6.4.28 (or, alternatively, the last fortran version of `HERWIG`), up to hadron decay, using `PYTHIA` default branching ratios. The resulting particles and hadrons were injected into a `CORSIKA` simulation, considering a 70° inclined shower set-up within the `U.S. Standard` atmospheric model, and allowing for their propagation and for further secondary hadronic and electromagnetic interactions, down to the Earth's surface.

The evolution of the muon yields of each shower as a function of the atmospheric depth is shown in fig. 2, considering both the case of EAS involving an intermediate MBH stage (set I, upper panel) and the case of standard EAS generated by p (set II, intermediate panel) or Fe primaries (set III, lower panel). Each solid or dashed line in each panel represents the evolution of the μ^+ or μ^- components of a single shower, respectively, whereas the average over all EAS of each set is showed by a thick solid line. One can see that the amount of fluctuation of the results of single showers around their average is similar in the case of set I and set II, while it is greatly reduced in case of set III. The spreading is partially related to the position of the first interaction of the cosmic ray primary with the atmosphere, that is sampled for all cases according to the standard `CORSIKA` procedure, providing a variable first interaction depth, in relation to the mean free path of the primary, which depends on its nature, its energy and the atmospheric properties. Actually, we adopted this same sampling strategy of the first interaction depth even for the events of set I, assuming that, even in case of formation of a MBH, the evaporated particles are all injected in the atmosphere at the same atmospheric depth as the primary CR interaction (*i.e.* we neglected the finite size of the MBH horizon, according to the fact that a MBH with radius larger than 10^{-16} m would have an evaporation time exceeding the age of the universe [39] and we assumed that the MBH propagation in the atmosphere is negligible, as it evaporates instantaneously).

Finally, the comparison between the average μ production depth profiles, obtained by averaging over all showers in case of set I, set II, and set III, respectively, is shown in the upper panel of fig. 3, from where it is clearly visible that the transient presence of a MBH can actually originate sizable deformations, somehow mimicking those generated by changing primary composition. Analogous differences in the shower profiles in presence and absence of a MBH intermediate state are registered by our simulations even in case of the electron and positron EAS components, whose averages are shown in the lower panel of fig. 3 for each of the three sets. In particular, $\langle X^{\ell_c}_{max} \rangle$ *i.e.* the average atmospheric depth where the maximum number of charged leptons of each flavour is registered, is located higher in the sky for the EAS of set I than for those of set II. Related to this, events of set I would manifest typical features of older showers, with a lower number of μ's reaching the detector arrays positioned on the Earth's ground, when compared to those of set II. On the other hand, in case of the Fe induced EAS of set III, the position of the maximum is even more shifted towards the upper part of the atmosphere, but the number of μ's produced and reaching the Earth's ground is larger. Thus a simultaneous measure of the number of μ's at the Earth's surface and of the X^{μ}_{max} position with a sufficient accuracy, could allow to discriminate among the three possibilities. Furthermore, it is still possible to distinguish between Fe and p + MBH showers, even in those cases in which their $\langle X^{\ell_c}_{max} \rangle$ are very close, by looking at the fluctuations around the average, RMS($X^{\ell_c}_{max}$), that appear larger in case of the events of set I than for those of set III, due to the different cross-section features.

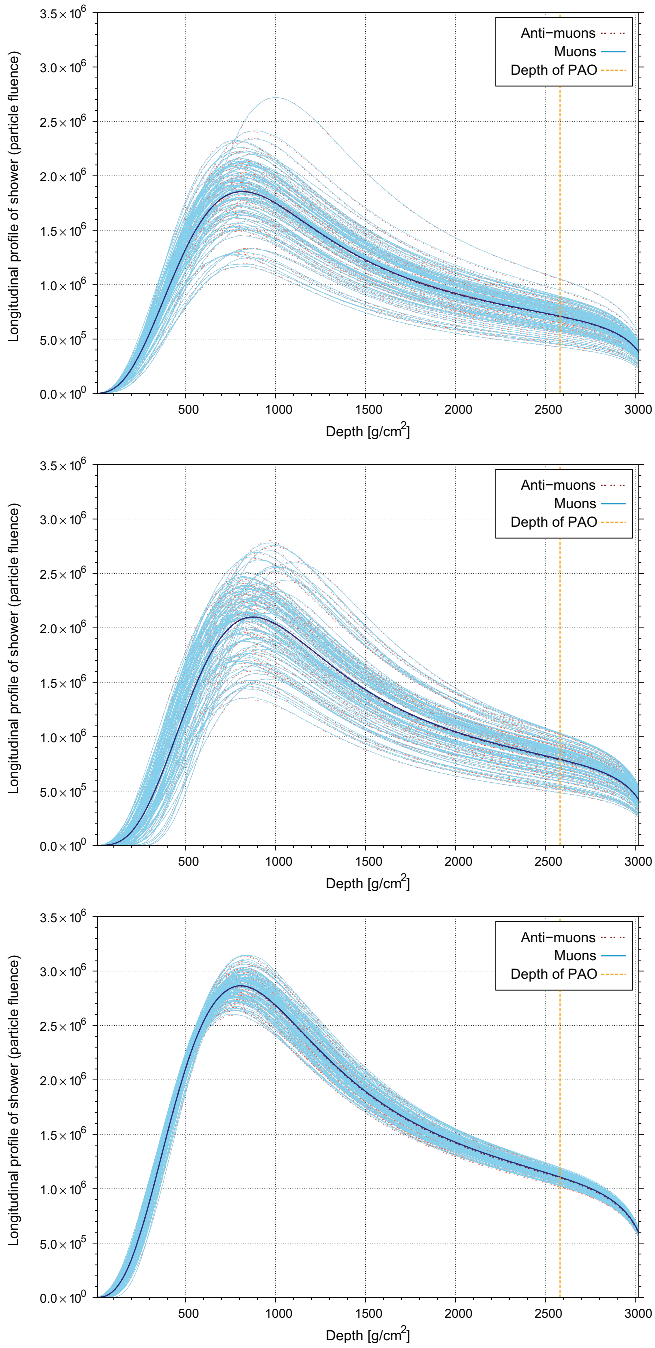

Fig. 2. – μ^- and μ^+ profiles (in unit of number of particles per shower) of $\sim$ 100 EAS events from set I (upper panel), set II (intermediate panel) and set III (lower panel), respectively, together with their average. The sea level corresponds to the maximum atmospheric depth at the right of the x axis. For reference, the atmospheric depth of the PAO for 70° inclined EAS is also indicated (vertical line).

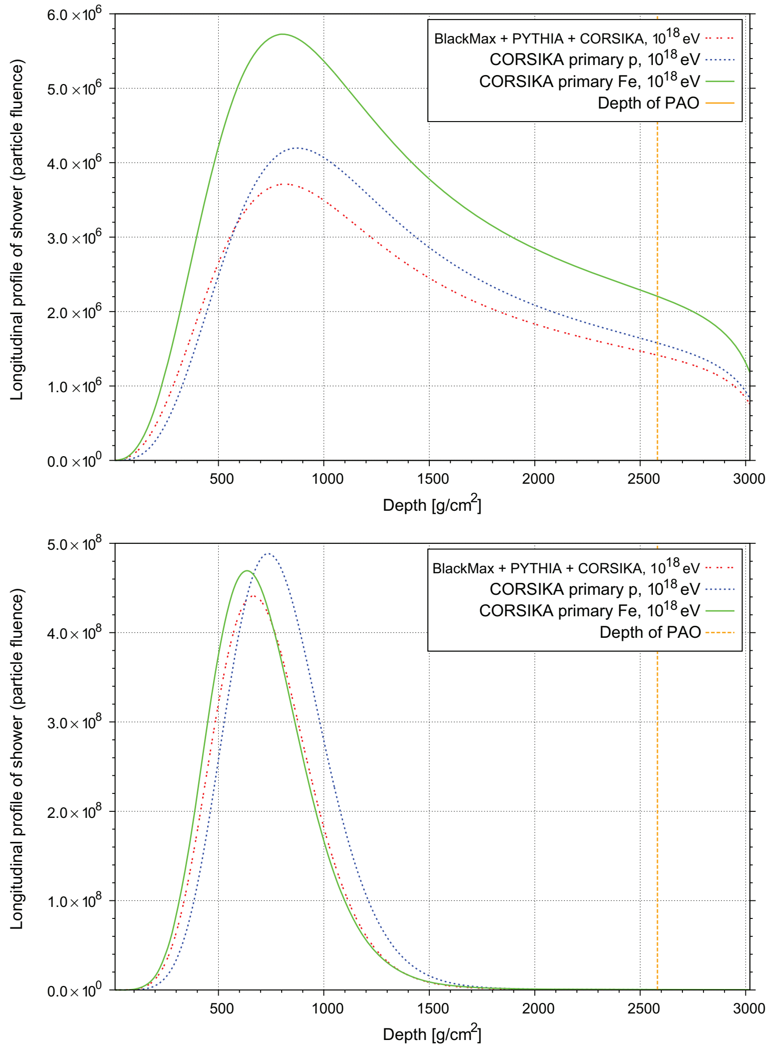

Fig. 3. – Average μ (top) and e (bottom) profiles (in unit of number of particles per shower) from events of set I (dashed line), set II (dotted line) and set III (solid line). The sea level corresponds to the maximum atmospheric depth at the right of the x-axis. For reference, the atmospheric depth of the PAO for 70° inclined EAS is also indicated (vertical line).

As a consequence, exploiting such kinds of differences in the EAS component profiles, and making comparisons of the predictions of simulations with the EAS experimental data (using all available measurements of $\langle X_{max} \rangle$, RMS(X_{max}) and of the μ number at the Earth's surface), we expect that it could be possible, at least in line of principle, to derive constraints on MBH states complementary to those already inferred at LHC. On the other hand, one of the most intriguing elements of this procedure concerns a rigorous assessment of the systematical uncertainties of the astrophysical measurements, that are certainly larger than those characterizing the much more controlled collider frameworks, and that will have to be properly taken into account in a statistical analysis aiming to provide limits on MBHs and the underlying gravity models.

5. – MBH detection perspectives: a qualitatitive discussion on specific signatures

While examples of differences between EAS passing through an intermediate MBH stage and Standard EAS have been provided in the previous section, by considering the most frequent case of the formation of a single EAS per primary event, here we briefly review some special topologies, involving multiple EAS per event, that have been proposed as promising channels (smoking guns) for the detection of MBH-induced EAS, and we discuss them in the light of our theoretical findings. Here we limit ourselves to a qualitative discussion, leaving exact quantitative statements to a dedicated work.

One of the first topologies presented in the literature as worth of exploration is the so called double-bang topology. This topology was first proposed in the context of high-energy neutrino astrophysics [40], as interesting for the detection of neutrino-induced EAS [41], in particular when the primary is a ν_τ (in which a ν_e or a ν_μ of astrophysical origin can transform due to neutrino oscillations) with energy of the order 10^{18} eV. The primary ν_τ could interact with a nucleon in the atmosphere by exchanging a charged-current quantum, giving rise to a τ lepton, accompanied by a hadronic remnant that initiates a first shower in the hard-scattering interaction region, on the one hand. On the other hand, the τ is a penetrating particle, characterized by a decay length much larger than the interaction length for the considered energies, that can decay before reaching the Earth surface either hadronically (in about 64% of the cases) or leptonically (in about 36% of the cases), giving rise to a second (hadronic or electromagnetic) EAS with a vertex displaced with respect to the first EAS, resulting in a so-called double-bang topology. The reason why this channel is interesting is the very peculiar signature, almost free from QCD backgrounds, characterized by two displaced maxima, located at different atmospheric depths, in the shower profile. This signature has been investigated by means of fluorescence detectors at the PAO, allowing to identify EAS profiles, complemented by information from surface detectors [42]. The last ones, in particular, are capable of collecting the products of the development of both showers reaching the Earth surface, if the showers are inclined enough. This topology has also been invoked as a possibly promising topology for the detection of MBH induced EAS [43, 44]. In this case the first bang would be originated by the evaporation of the MBH, that, in case a τ is present among the evaporation products, would be accompanied by a second bang originated by the decay of the τ. The practical feasibility of such a kind of study has been discussed by ref. [31] on the basis of theoretical predictions concerning EAS induced by MBHs, obtained by means of the `GROKE` Monte Carlo code for the description of the MBH evolution, interfaced to `PYTHIA` and `AIRES` for the simulation of EAS formation and propagation. Our simulations, done on the basis of a different (more updated) framework (`BlackMax` + `PYTHIA` + `CORSIKA`), essentially confirm the picture presented in ref. [31]. In particular, we would like to point out that, in line of principle, whereas in case of neutrino-induced showers, the energy window of the initial neutrino should be in a narrow range around 10^{18} eV, in order to have a second shower detectable, in case of a MBH intermediate state, a double-bang topology would require a higher energy of the primary, taking into account that a smaller fraction of the energy goes to τ leptons (the evaporation of a MBH gives rise to a collection of several particles, of the order of $\mathcal{O}(10)$ per event or even more, depending on the models and on the CM energy, differently from a charged-current interaction with just two particles in the final states, sharing the whole energy available in the CM). Additionally, the rate of this specific kind of events would be modified by the following elements: not always a τ is produced by the decay of a MBH (colored particles are preferred by Hawking evaporation with respect to the non-colored ones, due to the larger number of degrees of freedom), or, alternatively, more than one τ may be produced, taking into account that τ's can come both from the decay of heavy elementary particles (*e.g.* top quarks decaying in Wb pairs, with the W decaying leptonically) and from the decay of hadrons formed at lower energy scales after parton shower. We expect that these τ's can span different energy scales, according to their very different production mechanisms (in particular the hardest τ's come from the first of the two processes), and that, in case of a process with more than one τ, even a multiple-bang topology could, in line of principle, manifest itself. This may happen if τ's of different energies are produced, with the most energetic ones decaying deeper in the atmosphere. Alternatively, if two τ's of comparable energy would be produced (*e.g.* two τ's originated by the decay of two top quarks), the superposition of their showers could give rise to a single enhanced second bang. The frequency with which these specific phenomenona (multiple bangs, double enhanced bang) could occur, however, has to be precisely investigated by means of dedicated simulations. The amount of rotation of the MBH is a key parameter that could affect all these predictions and the accurate theoretical knowledge of the grey-body factors for graviton emission for a rotating black-hole in presence of extra-dimensions, is a fundamental missing piece for a correct estimate.

A further possibility that has been recently proposed is the possible formation of pairs of showers, with directions displaced by a small angle, arising from a different kind of phenomenon, *i.e.* the decay of a MBH dominated by quantum gravity effects, in just two particles or jets, moving oppositely in the CM frame of the collision between the partons from the cosmic ray and from the atmospheric nucleus, respectively [45]. According to Lorentz transformations, this corresponds to two showers developing at an angle $< \pi$ in the laboratory reference frame. If the angle between the two EAS is small enough, the footprints of this mechanism could be identified by means of surface detectors, looking at dishomogeneities in the shower front on the Earth surface, that would be characterized by two clusters centered in two different regions. This possibility may arise in case of a Quantum MBH, *i.e.* in case of a MBH whose mass is not too large with respect to the fundamental gravity scale ($M_{MBH} <$ very few $M_{gravity}$). In these conditions, according to theoretical speculations, the MBH does not thermalize during its evolution and thus does not evolve through a Hawking evaporation phase, leading to the production of a large number of (relatively) low-energy particles, but decays in a binary way. This possibility has first been proposed in the context of investigations at colliders [46, 47], where the decay products of a non-thermal MBH should be detected as back-to-back jets. However, its investigation in the framework of UHECR experiments is also important, especially if the LHC will be able to further constrain the fundamental gravity scale to higher values, *e.g.* by the runs at $\sqrt{s} = 13$ and $14\,\mathrm{TeV}$ foreseen within the next few years. Our Monte Carlo simulation framework, composed by `BlackMax` + `PYTHIA` + `CORSIKA`, at present is addressed to the description of classical or semi-classical MBHs. On the other hand, to accurately study the possibility of Quantum MBHs and investigate the topology described above, a further step is required, *i.e.* interfacing an alternative Monte Carlo code like `QBH`, specifically designed for studies of Quantum Black Holes and so far used for analyses at colliders, to `PYTHIA` and `CORSIKA` to perform the EAS physics simulations to be compared to the experimental data. We are working also in this direction.

6. – Summary and conclusions

In this paper we investigated the possibility that a transient MBH state, as predicted in TeV-gravity models involving the existence of extra-dimensions where gravity mainly propagates, appears during a primary CR interaction with the Earth's atmosphere, showing that it may lead to sizable modifications of the properties of the EAS formed after its evaporation, when compared to the SM EAS in the usual 4-dim scenario neglecting gravity effects in primary interactions. This study was performed by interfacing current state-of-art event generators for the description of the various steps of the EAS formation process, from primary interactions leading to the MBH formation and evaporation, to the generation of EAS propagating down to the Earth surface, by creating a complex numerical framework embedding different MC codes. As a proof of concept, the results shown in this paper refer to simulations performed within a fixed set-up, among many different possible choices for the input parameters (including both those specific to the CR framework, like the CR primary energy spectrum, composition, direction and the atmospheric modelling, and those concerning MBH physics and the underlying geometry, like the MBH properties, the grey-body factors and the number of extra-dimensions), but the framework we have set up allows indeed for a more systematical study, with scans of the input parameters in plausible intervals, that we plan to perform in a next paper. If differences of at least the same order of magnitude of those seen in this paper between the standard EAS profiles and the profiles in the presence of MBHs will be confirmed in a large portion of the parameter space, we are confident that further comparisons with EAS experimental data could allow to set limits on MBHs (and, as a consequence, on the theoretical models predicting them) complementary with respect to those already set by the LHC experiments.

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